

Dynamo-Driven Outflows in Pre-Planetary Nebulae

Eric G. Blackman

Physics & Astronomy Dept., Univ. of Rochester, Rochester NY, 14627

Abstract. The plethora of asymmetric planetary nebulae and the curiously high momenta of pre-planetary nebula outflows suggest that rotational energy is extracted from the engines. Magneto-rotational outflows driven by dynamos might be operating therein. I summarize scenarios involving (a) an isolated AGB star and (b) a binary. The efficacy of (a) requires re-establishing differential rotation over the AGB star's lifetime, whereas (b) delivers the angular momentum at the end of the AGB phase when needed, and may involve turbulent disks. Both can produce fields that drive outflows of the required mechanical luminosity and momentum, though weak points and open questions require further study.

1. Observations Suggest a Role for Magneto-Rotational Outflows

Powerful anisotropic outflows appear in a wide range of astrophysical sources and magneto-rotationally driven models are often a favored explanation. Maybe asymmetric outflows (e.g. Balick & Frank 2003) in planetary nebulae (PPNe) and pre-planetary nebulae (PPNe) also involve dynamically important magnetic fields (Aller 1958). Magneto-rotational driving is particularly appealing for PPNe winds which are more powerful than PNe winds: The observationally inferred rates of mechanical momentum and energy deposition for PNe are (Kwok 2000) $\dot{\Pi} \sim 10^{27} (M_{pn}/0.04M_{\odot})(v_{pn}/40\text{km/s})(\Delta t_{PN}/10^4\text{yr})^{-1} \text{ erg/cm}$, and $\dot{E} \sim 10^{34} (\dot{\Pi}/10^{27}\text{erg/cm})(v_{pn}/40\text{km/s}) \text{ erg/s}$, where M_{pn} is the swept up mass in the PN, v_{pn} is the speed of this mass, and the acceleration time $\Delta t_{PN} \leq$ age of the PN. But observations of PPNe (Bujarrabal et al. 2001) reveal values up to $\dot{\Pi} \lesssim 3 \times 10^{29} (M_{ppn}/0.5M_{\odot})(v_{ppn}/200\text{km/s})(\Delta t_{ppn}/10^3\text{yr})^{-1} \text{ erg/cm}$, and $\dot{E} \lesssim 10^{37} (\Pi/10^{40}\text{erg/cm})(v_{ppn}/200\text{km/s})\text{erg/s}$ where the acceleration time $\Delta t_{ppn} \ll$ age of the PPN. The PPNe wind momenta are often $\sim 10^3$ times that carried by radiation even when multiple scattering is considered.

A large scale magnetic field can act as a drive belt that extracts rotational energy to drive a wind from the engine where the field lines are anchored (e.g. Spruit 1996). When the engine is a star, the extraction spins the star down. When the engine is an accretion disk, a fraction of the accretion luminosity gets redirected into the wind. In the Blandford & Payne (1982) type model, mass outflow is driven by the toroidal magnetic field pressure gradient along poloidal field lines, though in the rotator's co-rotating frame near the footpoints, the processes can be thought of as centrifugal launching along favorably inclined poloidal field lines. Consideration of magnetically mediated outflows raises nat-

ural questions in the PPNe/PNe context: Where do the required fields come from? How do these mechanisms work for single star or binary/disk systems? Are the outflow powers and momenta consistent with the observations?

2. Why Would Dynamos be Needed to Produce the Fields?

Convection driven and magneto-rotationally driven MHD turbulence (Balbus & Hawley 1998) are fully developed in in AGB stars and in accretion disks (the two relevant environments) respectively. Large scale magnetic fields can then experience turbulent diffusion so intense that the field is not flux-frozen on the relevant dynamical or advection time scales (Lubow et al. 1994; Blackman & Tan 2003 (BT)). This highlights the need for dynamo amplification. The fields also be large enough to avoid diffusing before escaping to the corona where they are needed. In coronae, the fields can further open up. Coronal loops which carry magneto-centrifugal winds should be at least as large as the radial scale of the anchoring rotator so that material can be accelerated to super-Alfvénic velocities before reaching the loop-tops and avoid sliding back down.

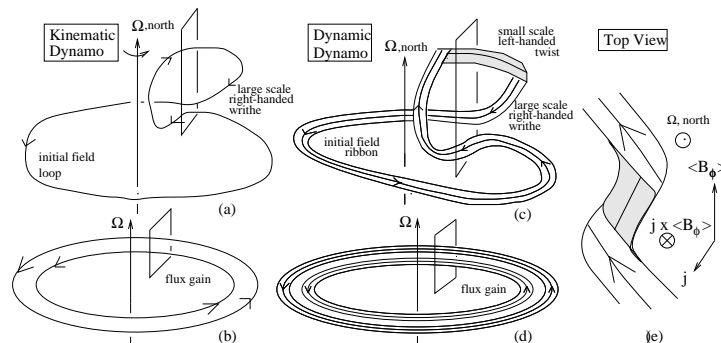
3. Some Recent Developments in Large Scale Dynamo Theory

Dynamos amplify or sustain magnetic fields by draining energy from random and shear motion. Nonhelical (direct) dynamos amplify fields at wave numbers $k \geq k_f$ whereas helical (inverse) dynamos can also amplify fields at $k < k_f$, where k_f is the smallest wavenumber at which the flow is turbulent. Here “helical” refers to whether the driving turbulence possesses a non-vanishing pseudoscalar helicity such as kinetic helicity $\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle$, where \mathbf{v} is the turbulent velocity, and the brackets imply averaging within a hemisphere. The nonhelical dynamo increases magnetic energy as the turbulence stretches magnetic field lines in a nearly random walk, but it is the helical dynamo (e.g. “ $\alpha_d \Omega$,” see Moffatt 1978) which produce the large scale fields needed for outflows. Helical turbulence can be supplied by convection in a star, or by the magneto-rotational instability in a stratified disk (Brandenburg et al. 1995; Brandenburg 1998; BT).

While 3-D MHD simulations are essential for understanding dynamos, they are not always practical for modeling. For the latter, mean field theory (e.g. Moffatt 1978) is used. Here the field is broken into mean and fluctuating components. The helical dynamo growth coefficients become correlations of fluctuating quantities, and the mean field evolution is solved for. Traditional treatments do not dynamically determine the saturation strength of the large scale field; they either take the growth to be steady (=kinematic theory), or presume a form of quenching by the growing magnetic field without conserving magnetic helicity, a fundamental invariant of ideal MHD. A recent theory which alleviates these limitations by including the dynamical evolution of the velocity and magnetic helicity (Blackman & Field 2002) is illustrated below.

Fig. 1 below (from Blackman & Brandenburg 2003) shows the helical $\alpha_d \Omega$ dynamo in a rotating northern hemisphere. The kinematic theory is shown in (a) and (b) while (c), (d) and (e) show the dynamic theory. (a): To conserve angular momentum, rising (falling) blobs in a stratified medium twist in the opposite (same) sense to the underlying rotation. This implies a non-vanishing

$\langle \mathbf{v} \cdot \nabla \times \mathbf{v} \rangle$, averaged in a given hemisphere. This “ α_d ” effect implies that a large scale toroidal loop in the northern hemisphere incurs a right-handed writhe, and a radial field component as it rises. (b): Differential rotation (the “ Ω ” effect) at the base of the loop shears the radial component, amplifying the toroidal field. Dissipation or ballooning/opening of the top part of the loop allows for a net flux gain through the rectangle. (c): Same as (a) but now with the field represented as a ribbon. The right-handed writhe of the large scale loop is accompanied by a left-handed twist along the tube, incorporating magnetic helicity conservation. (d): Same as (b) but with field represented as ribbon/tube. (e): Top view of the combined twist and writhe. The backreaction force which resists bending is the small scale twist. Diffusing the top part of the loops allows a net flux generation in the rectangles of (a)-(d), and helps alleviate the backreaction.



The dynamic role of magnetic helicity is seen in simulations (Brandenburg 2001) and modeled analytically (Field & Blackman 2002; Blackman & Field 2002). Although the small scale magnetic helicity growth drives the helical dynamo to a steady state, the large scale field grows large enough for most astrophysical applications. Application of these principles to disks and stars with boundaries is work in progress. In addition, buoyancy rather than kinetic helicity may be the initial driver of the helical α_d effect in disks (Brandenburg 1998). This affects the initial sign of α_d in each hemisphere, but magnetic helicity evolution remains a key to understanding the saturation.

4. Single Star Scenario: AGB Dynamo and Magnetic Explosion

This scenario (Blackman et al. 2001 (BFMTV)) begins with a main sequence (MS) star $\sim 3M_\odot$ of rotational speed ~ 200 km/s. At the end of the MS lifetime, the core collapses and the envelope expands, and angular momentum is assumed to be conserved on spherical mass shells. The rotation profile satisfies $\Omega \propto 1/r^2$ which is then combined with a numerical AGB stellar model (SDK1401, Steve Kawalar, personal communication). In SDK1401, the convection zone extends from the outer stellar radius 5×10^{12} cm down to the core radius $r_c = 9 \times 10^{10}$ cm. At the “interface” between the core and the envelope, $\Omega \sim 2 \times 10^{-5}$ cm/s.

The combination of a strong differential rotation layer and overlying convection zone may lead to an “interface dynamo” (e.g. Markiel & Thomas 1999). Here the poloidal field is generated by a helical α_d -effect layer in the convection zone. Diffusive transport (or turbulent pumping; Tobias et al. 1998) bleeds the poloidal field to the shear layer beneath the convection zone where it is further

amplified by linear stretching (“ Ω ” effect). BFMTV applied the code of Markiel & Thomas (1999) to the AGB star, (The α_d formula used was consistent with magnetic helicity conservation.) At $r \simeq r_c$ the saturated field is $B \sim 5 \times 10^4$ G.

The scenario requires this dynamo to be steady for $\sim 10^6$ yr until the envelope of the AGB star is radiatively driven away in the late AGB stages. Eventually, the density falls such that the field can no longer be stored: Turbulent pumping can be gauged by assuming it to be proportional to a fixed convective energy density transfer rate ρv^3 . As ρ decreases, v increases and the turbulent pressure, $\propto \rho v^2$, decreases with decreasing ρ , eventually dropping below $B^2/8\pi$ at the core. At this point, a “magnetic explosion” associated with toroidal pressure could ensue and drive the PPNe outflow. The magnetic explosion is driven by Poynting flux, and surface integration reveals a maximum mechanical luminosity (Blackman, Frank, Welch 2001 (BFW)) $L_m \sim 10^{37} \left(\frac{B}{5 \times 10^4 \text{ G}}\right)^2 \left(\frac{\Omega_c}{10^{-5} \text{ s}}\right) \left(\frac{r_c}{r_\odot}\right)^3$ erg/s, where r_c and Ω_c are the core radius and angular speed respectively. This high L_m lasts for a magnetic spin down time of the star (~ 100 yr, starting after the envelope is lost) and then decays exponentially. The asymptotic outflow speed should approach $v_\infty \sim \Omega_0 r_A$, where r_A is the Alfvén radius, which can be less than or comparable to the escape speed $v_{esc} \sim 520 (r_c/10^{11} \text{ cm})^{1/2} (M_*/M_\odot)^{1/2}$ km/s, depending on r_A . Matt et al. (2003) (these proceedings) have simulated a magnetic explosion. The above results are consistent with the requirements of PPNe (see Sec. 1). (Imai et al. (2002) have observed a collimated AGB jet.)

Unfortunately, the present interface dynamo models, while including a saturation of the α_d effect, do not include saturation of the Ω effect. In reality, amplification of the magnetic field at the shear layer drains shear energy, and transfers angular momentum from the core to the envelope, slowing down the core within ≤ 100 yr, unless the differential rotation is re-seeded throughout the 10^6 yr lifetime of the AGB phase. This is important because matching the PPNe observations requires the field to be anchored in a rapidly rotating core.

The so called “Lambda effect” (c.f. Rüdiger 1989) might be able to re-seed the differential rotation. This mechanism involves the interplay between the overall rotation and asymmetric convection to produce a steady-state rotation profile. The helical interface dynamo has to be solved with a dynamically coupled Lambda effect. This awaits attention, but note that there is enough energy in the fusion driven turbulent convection to sustain the differential rotation: The turbulent energy density can be calculated from the aforementioned AGB stellar model SDK1401 and the result is (J. Nordhaus personal comm.) $\sim 5 \times 10^{43}$ erg. This can be compared with the magnetic field energy in the shear layer from BFMTV, which is $E_m \sim 10^{41}$ erg, which in turn is about 1/8 the shear energy in the interface layer. Thus only $\sim 2\%$ of the energy from the convection needs to be steadily drained into the desired differential rotation.

5. Binary Scenarios: Disk Dynamos and/or Primary Core Spin-up

Binary scenarios do not suffer from the sustained shear problem just discussed because they deliver the angular momentum near the end of the AGB phase (e.g. Soker 1998), just when needed to drive the outflows.

Such angular momentum transfer could occur in the late AGB stage by common envelope (CE) evolution (e.g. Iben & Livio 1993), as the secondary star penetrates the distended AGB envelope and transfers orbital angular momentum to it. The AGB star can shed 80% of its mass within years of the onset of CE, depending on the binary parameters. During the shedding, the companion spirals nearer to the core. While accretion of envelope material can occur onto the secondary (e.g. Morris 1987; Soker & Livio 1994; Mastrodemos & Morris 1998), much larger (needed) accretion rates arise when an accretion disk forms around the primary via disruption of the secondary (Reyes-Ruiz & López 1999). Favored systems for this mode of accretion involve an evolved AGB star with mass $2.6 \leq M_*/M_\odot \leq 3.6$, a secondary with mass ($\leq 0.1M_\odot$), and the initial binary separation $\geq 200R_\odot$. Reyes-Ruiz & López (1999) find that the disk accretion rate onto the residual primary core evolves in time (after an initial ~ 1 yr viscous adjustment period) as $\dot{M}_d = \dot{M}_{do}(t/\text{yr})^{-5/4}M_\odot \text{ yr}^{-1}$. Typical values of the initial accretion rate $\dot{M}_{do} \simeq 10^{-3}\dot{M}/\text{yr}$.

Once the disk forms, a helical disk dynamo (e.g. Pudritz 1981; Brandenburg et al. 1995; Reyes-Ruiz & Stepinski 1995; Campbell 2000; BT) provides the mean field strengths from which one can determine the magnetic luminosity L_m , available to drive an outflow. This can be estimated as the integrated Poynting flux flowing through the disk surface (or, the Poynting flux through the Alfvén surface (BFW; Frank & Blackman 2003 (FB)). Tan & Blackman (2003) find $L_m \sim \overline{B}_p \overline{B}_\phi \Omega_i r_i^3 \sim \frac{\alpha_{ss}^{1/2} G \dot{M}_d M_*}{r_i} \sim 10^{37} \left(\frac{\alpha_{ss}}{0.1}\right)^{1/2} \left(\frac{M_*}{M_\odot}\right) \left(\frac{r_i}{10^{11}\text{cm}}\right)^{-1} \left(\frac{t}{1\text{yr}}\right)^{-5/4} \frac{\text{erg}}{\text{s}}$ where $\alpha_{ss} \lesssim 0.1$ is the assumed disk viscosity parameter (Shakura & Sunyaev 1979), r_i is the inner radius, and c_s and Ω_i are the sound and rotation speeds there. The \dot{M}_d enters because $\rho \propto \dot{M}_d$, and the mean surface poloidal and toroidal fields satisfy $\overline{B}_p \sim \rho^{1/2} \alpha_{ss} c_s$ and $\overline{B}_\phi \sim \rho^{1/2} \alpha_{ss}^{1/2} c_s$. A calculation of acceleration along a poloidal field line gives the asymptotic velocity $v_\infty \sim \Omega_i r_A \sim 2^{1/2} \Omega_i r_i \sim 730 (M_*/M_\odot)^{1/2} (r_i/10^{11}\text{cm})^{1/2} \text{ km/s}$ (FB). For a rotationally supported disk, the asymptotic wind velocity is always near or greater than the escape speed. The mechanical luminosity and momentum delivered are consistent with the PPNe requirements of Sec. 1.

Rather than form a disk as just described, an alternative is that the companion could spin up both a slowly rotating core and envelope, leading to significant differential rotation between the two (assuming a turbulent viscosity in the envelope). This could rejuvenate the interface dynamo of Sec. 4 during CE in the late AGB stage just when needed. The time scales of spin-orbit synchronization (Zahn 1977), envelope ejection, and viscous dissipation (Iben & Livio 1993) must be compared, but this alternative might mean that a wider range of binary systems could produce magneto-rotational outflows.

6. Open Questions

Asymmetric outflows in PPNe and PNe signature the transport of angular momentum, and magnetically mediated outflows may produce the required power and momenta. Maser (Miranda et al. 2001; Vlemmings et al. 2003) and core X-ray (Kastner et al. 2003) observations loosely support this general paradigm.

However, key unresolved issues remain: (1) Is there a need for collimated outflows from both the AGB star and disk? Are both self-collimated or does the latter collimate the former? What might misaligned nested winds produce (BFW)? (2) Do all PPN/PNe produce collimated jets when the sources are young? (3) Large scale nonlinear dynamo theory is in its infancy for realistic boundary terms. How do helical dynamo fields open up and dynamically relax in the coronae? (4) How far is momentum carried as Poynting flux? (e.g. hydro-magnetic “fling” models vs. magnetically dominated “spring” models, or nested hybrid models? Ustyugova et al. 2000). (5) MHD jet simulations have been separate from MHD dynamo simulations. Simulations capturing both together have not been done, though using a dynamo produced field and then simulating the outflow provides encouraging results (von Rekowski et al. 2003). Non-steady calculations are important in this context. (6) The single AGB wind scenario will only work for PPNe if convection + rotation can steadily re-seed the differential rotation to ensure a large enough Poynting flux at the end of the AGB phase. If not, binaries may be absolutely required for asymmetric PNe and PPNe (e.g. Soker & Livio 1994; Soker 2001). Stellar evolution models which include magnetic fields and rotation are needed. (7) To what extent are the strong outflows in PPNe correlated with the presence of binaries? Binaries with brown dwarfs or planets are not easily detected, but are favored for accretion around the AGB core. (8) How restrictive are the initial binary parameters for which common envelope evolution simulations (Demarco et al. 2003) would produce a suitably accreting disk to power PPNe? Is this relaxed by the scenario at the end of Sec. 5? (9) Consequences of internal dynamo produced fields for surface X-ray emission in AGB stars and disks need more study. (10) Could winds from the primary vs. secondary disks be distinguished by abundance differences (FB)?

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